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REPORT A64-13

EXPLOSIVE WELDING

by

H. J. ADDISON, Jr.

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AMCMS Code 5025.11.842

U.S. ARMY MUNITIONS COMMAND

UNITED STATES ARMY
FRANKFORD ARSENAL
RESEARCH & DEVELOPMENT
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AMCMS Code 5025.11.842
DA Project 1-A-0-24401-A-110

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May 1964

PAPER NUMBER 64-MD-47

Explosive Welding

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Explosive welding occurs when adjacent surfaces of appropriately positioned metals are properly thrust together by energy released from an explosive source. The procedure consists essentially of locating the metal members being welded between an explosive charge and an anvil with the lower member resting on the anvil. Explosive welding can be used for spot and seam welding and cladding. Lap, tee and edge joints (such as is experienced in cladding) have been fabricated. Corner and butt joints are feasible. Tensile-shear strengths approaching that of the base metal have been obtained in various materials in seam-welded lap joints. Explosive spot welds have failed outside the nugget. Explosive welding is feasible and offers possibilities as a future fabrication method.

Contributed by the Machine Design Division and presented at the Design Engineering Conference and Show, Chicago, Ill., May 11-14, 1964, of The American Society of Mechanical Engineers. Manuscript received at ASME Headquarters, April 7, 1964.

Written discussion on this paper will be accepted up to June 15, 1964.

Copies will be available until March 1, 1965.

Explosive Welding

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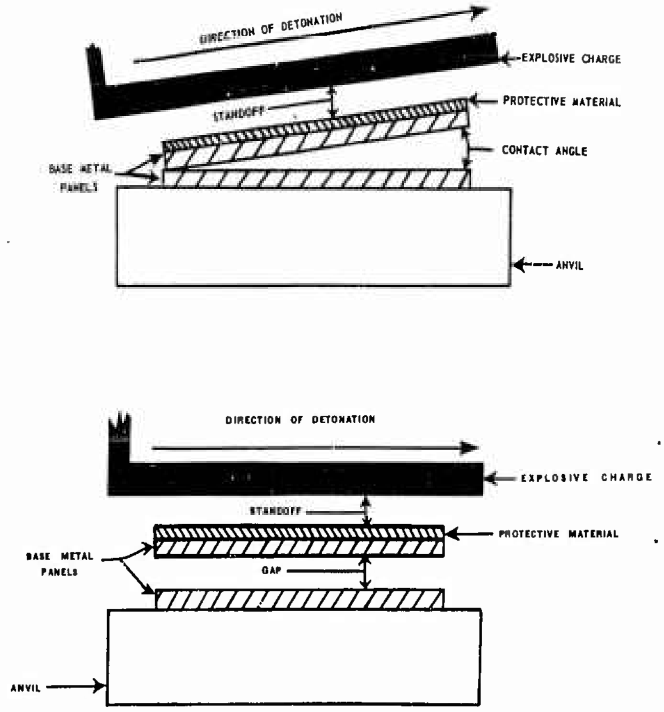

Fig. 1 Schematics of explosive welding. A (top): Angular technique; B (bottom): Gap technique

Explosive welding is a relatively new joining process that is being studied by an increasing number of organizations. With this process, welding occurs when the adjacent surfaces of the metals to be joined are oriented properly and projected together by energy released from an explosive source. Generally, no effort is made intentionally to provide heat to the welding operation although some heat may be generated in the weld owing to the absorption of energy. In contrast with fusion welding processes, therefore, explosive welding produces little or no melting at the weld interface.

These characteristics suggest several important advantages. These are (a) the ability to weld similar and dissimilar metals that may otherwise be difficult to join by fusion welding processes because of the deterioration of weld or base metal properties, (b) the welding of relatively large surface areas of sheets and plates such as a cladding type of operation, (c) the welding of configurations that may not be readily joined by other more conventional methods, and (d) the possibility of utilizing the process in field fabrications where the location may be inaccessible to other processes.

Most of the published reports on explosive welding have provided information on the dynamic characteristics of the operation, the mechanism of the weld and feasibility of welding various metals and alloys. Also, at least one investigator (1)[1] has reported the influence of certain welding variables on the mechanical properties of welded joints. Although explosive welding can be considered in the early stages of development, attention is being given to a few applications such as the cladding of sheet and plate. At least one organization reportedly is including the explosive cladding of alloys among its commercial activities.

It is likely that explosive welding will be used for many specialized applications as its possibilities become more apparent. Designers as well as fabricators, therefore, should have an awareness of the process, its characteristics and its state of development so that its position and capability with respect to other joining processes can be anticipated properly when considering the design and construction of future assemblies. It is the intent of this paper to present this type of information as reflected particularly by the author's work.

WELDING PROCEDURES

The principal features of explosive welding procedures are illustrated in Figs.1A (1) and 1B. The difference between the two illustrations is the positioning of the base metal members or panels to be welded. In Fig.1A, the panels are placed at an angle to each other forming a "contact angle". The second technique, Fig.1B, however, is a setup wherein the panels are positioned parallel to each other. The distance between the members has been called the gap; thus, the name "gap technique".

Other components of the welding setup are essentially the same. The panels are located between an anvil and the explosive charge with the lower panel resting on the anvil. The purpose of the anvil is to absorb energy generated within the panels during the welding operation. A protective or buffer material is placed over the up-

1 Numbers in parentheses designate References at the end of the paper.

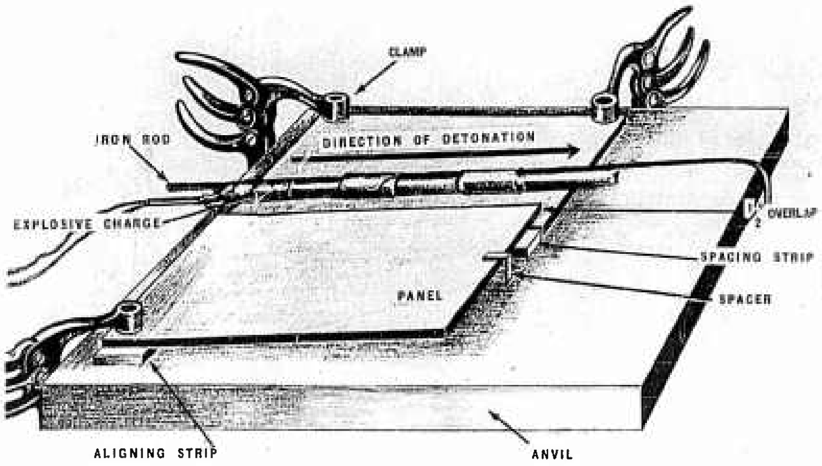

Fig. 2 Angular technique

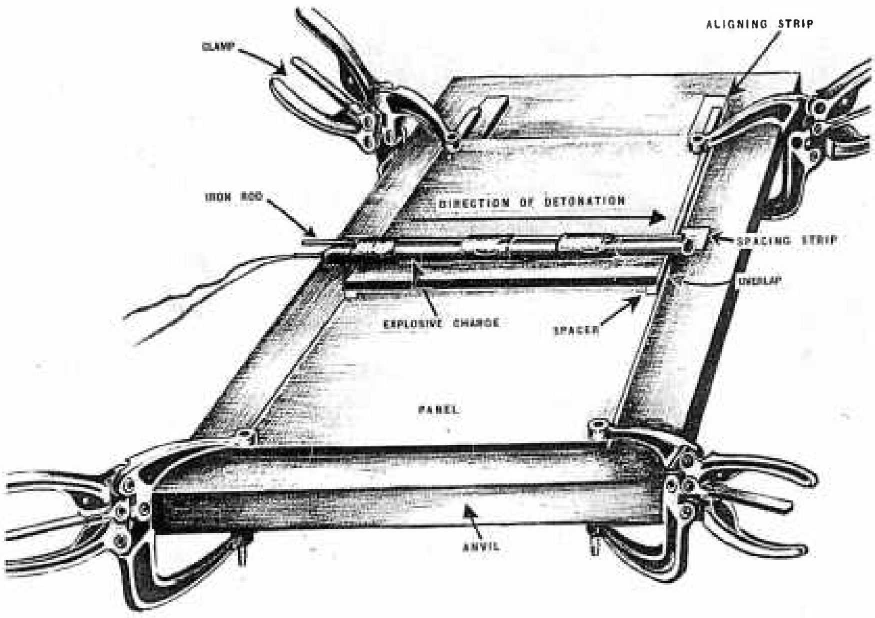

Fig. 3 Gap technique

per panel to minimize pitting and gouging of the surface. The distance between the explosive and the protective material is usually referred to as the "standoff". When the standoff is zero, that is, when the explosive charge is in contact with the protective material or top panel, the procedure is called a "contact operation". The procedure is referred to as a "standoff operation" when the charge is exploded at a selected distance away from the protective material and panel. In this situation the impulsive force passes through an energy-transmitting medium such as air or water to the top panel. Contact operations usually are used for welding bulk parts and plates whereas standoff operations having a short standoff are suitable for cladding or joining sheet and foil (2). The angular or the gap technique can be used with either operation.

Two specific welding setups used with these techniques are shown in Figs.2 and 3. In both instances, lap-welded specimens were prepared by clamping the two panels to the anvil. Primacord consisting of 400 grains of PETN per foot was taped to an iron rod for alignment and positioned parallel to the top panel over the area to be welded. A spacing strip was located as shown in the drawings to prevent the upper panel from being severely deformed or sheared along the edge of the overlap when thrust against the lower panel.

Spacers were used to obtain the proper angle or gap. In the angular technique, the top panel was bent to form an angle slightly greater than

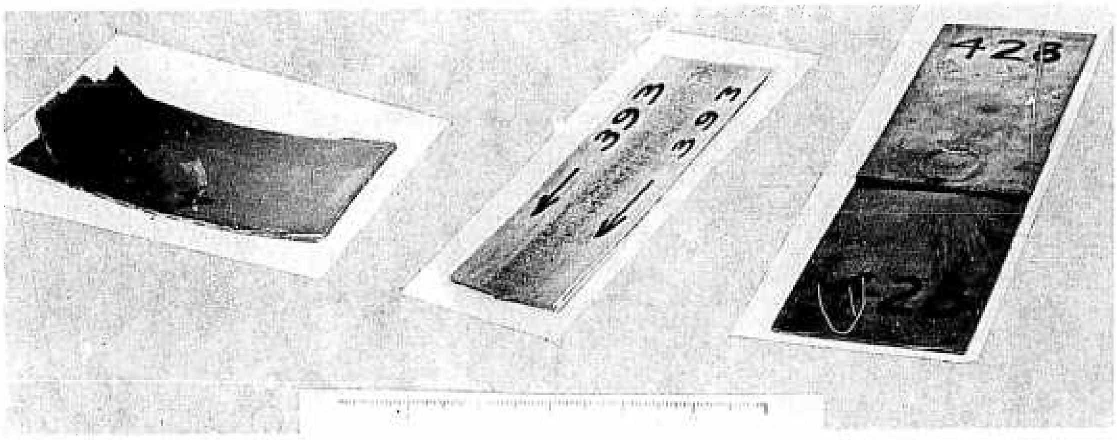

Fig. 4 Types of explosive welds. Left: area weld; middle: seam weld; right: spot weld

that which was desired. The spacer was then used to clamp the panel in the correct position. The spacer is displaced in the illustration to show the overlap but was actually over the overlap to assure alignment.

The distance separating the panels in the gap technique was obtained with shims. Dimpling of the top panel also has been used to provide the gap thereby eliminating the need for shims. Although early investigations were performed in water, air has been found to be a satisfactory energy-transmitting medium.

In welding 1/16-in. 2024-T3 aluminum-alloy sheet using the angular setup, a 1/2-deg contact angle and a 1/8-in. standoff produced weldments having tensile-shear strengths approaching the base-metal strengths. When the same material was welded with the gap technique, the best results were obtained using a gap or panel opening of 0.010 in. and a standoff of 1/8 in. It was noted that the gap technique provided somewhat more consistent mechanical properties along the full length of the weld.

Although Primacord was used in the foregoing work, other explosives, such as sheet explosives, in various forms and shapes have been tried using slightly modified procedures. The choice of explosive and shape of the charge is determined, among other factors, by the type of weld that is to be made.

TYPES OF WELDS

Explosive welding, because of the nature of the process, lends itself particularly to the joining of sheet or plate surfaces as in an overlap or cladding situation. Investigators, in studying explosive welding, have made at least three types of welds. These are area, seam, and spot welds. An area weld in this instance, as opposed to a seam weld, refers to a bond made between the entire mating surfaces of the two members. Fig.4 shows these three welds.

Area Weld

An area weld is represented by the specimen on the left in Fig.4. This specimen was made from two 1/16-in-thick, low-carbon steel panels using the angular technique. The panels are joined essentially throughout their width and length except for an obvious portion along the far edge. This specimen, in view of the separation, conveniently shows the two panels that were joined. Incomplete welding such as is shown can be minimized by changes or refinements in the welding procedure. This type of weld has received more attention by a number of organizations than other explosive welds. Major uses include clad and laminated materials.

Seam Weld

The seam weld represented by the middle specimen in Fig.4 was made down the center of the two panels. Both panels were 1/16-in-thick, 2024-T3 aluminum alloy, which is a high-strength, heat-treatable material. In this specimen, the overall width of the weld interface was approximately 1/2 in. The seam weld can be widened by appropriate changes in procedure without experiencing gross melting at the interface or thermal deterioration of the heat-affected zone often characterized by many other welding processes.

Spot Weld

A spot weld is shown at the right in Fig.4. The base material was 1/16-in-thick, tough pitch copper. Although this material is considered extremely difficult to resistance spot weld, it was explosively spot-welded without difficulty.

The diameter of an explosive spot weld may be

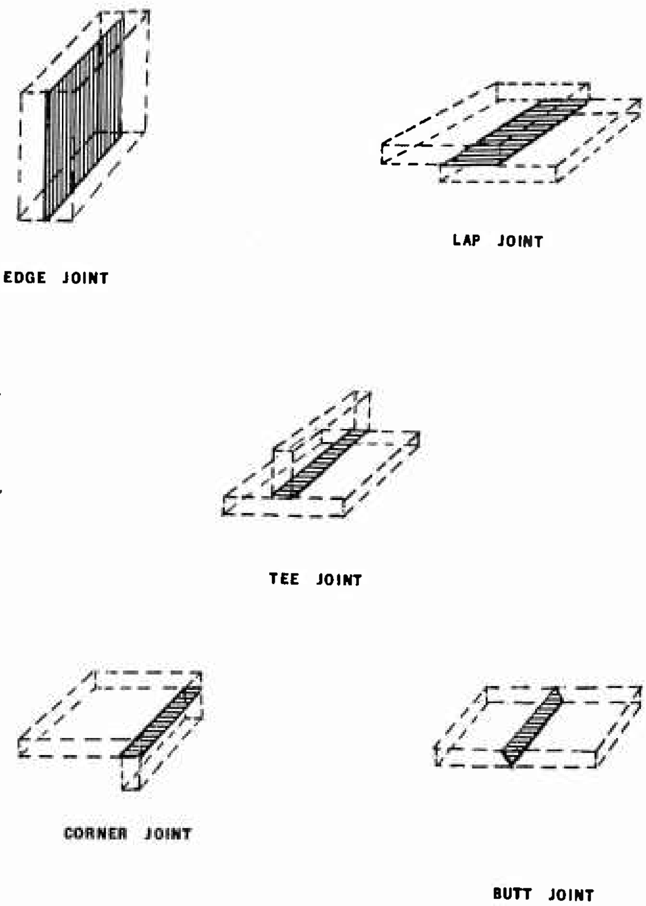

Fig. 5 Weld joints

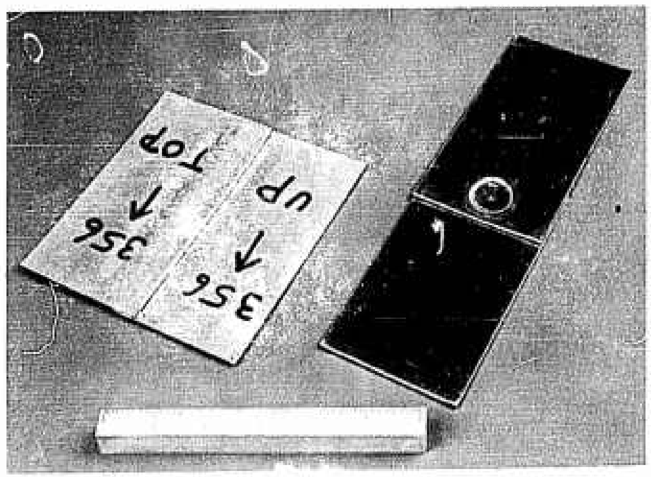

Fig. 6 Explosively welded lap joints in 1/16-in. aluminum alloy 2024-T3. Left: seam weld; right: spot weld

varied over a wide range by using appropriate explosive charges. This is an important attribute since the load-carrying capacity of a spot weld generally increases with its diameter, provided other factors are held constant.

TYPES OF JOINTS

There are five basic weld joints (3) available to the designer. These are:

1 Edge joint.
2 Lap joint.
3 Tee joint.
4 Corner joint.
5 Butt joint.

These joints, Fig. 5, have had many variations conceived to satisfy individual requirements of different assemblies.

The selection of a joint is usually done after considering a number of factors including the cost of fabrication, geometry of the weldment, distribution and magnitude of the stresses throughout the assembly and accessibility of the joint. Another important factor is the welding process since it must be capable of making the joint. Recent work has indicated that all of the basic joints in one form or another are at least feasible with the explosive welding process.

Edge Joint

The explosive welding process, using area welding procedures, is particularly suited to the edge type of joint, used in cladding.

Lap Joint

A considerable amount of data has been reported on the mechanical properties of explosively welded lap joints (1) indicating the applicability of the process to this type of joint. Two explosively welded lap joints are shown in Fig. 6. These joints were made using the gap technique. As can be observed, one joint was made with a spot weld. The other, however, is either a seam or area weld depending essentially on whether the entire width of the overlap is intentionally bonded.

Tee and Corner Joints

Very little information has been published on the explosive welding of tee and corner joints, but some work apparently has been conducted. Structural tee shapes reportedly were made in aluminum 6061-T6 (4) and Holtzman (5) has indicated that tee joints can be explosively welded. In view of the apparent success with the tee joint, it is likely that corner joints could also be produced with modified procedures.

Butt Joint

The modified butt joint (scarf joint) shown in Fig. 5 may, more than other butt joint, be explosively weldable since its interface could conceivably be oriented properly with the explosive charge using current techniques. The investigations suggest that joints of this type might be welded, although there has been no information re-

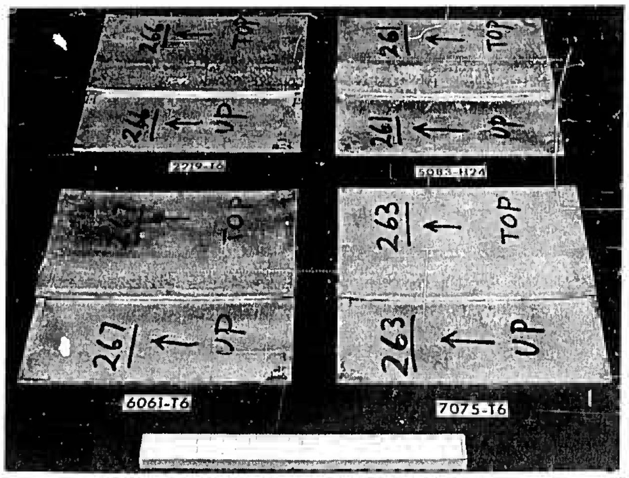

Fig. 7 Explosively seam welded, lap joints in aluminum alloys

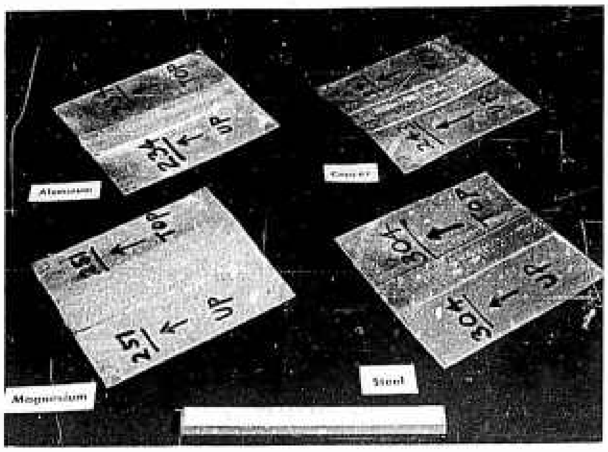

Fig. 8 Explosively seam welded, lap joints in four base metals

ported that butt joints have been successfully made.

EXPLOSIVELY WELDABLE BASE METALS

A number of base metals have been explosively welded. These include aluminum and its alloys, nickel alloys, refractory metals, gold and silver, copper and its alloys, as well as low-carbon and alloy steels in various combinations (1-3, 6-10).

There has been very little information published on the weld properties of these materials and, therefore, the author has been conducting an investigation directed toward obtaining tensile shear data on various metals and alloys. Several lap-welded specimens of different alloys are shown in Figs.7 through 9. Figs.7 and 8 are seam welds whereas Fig.9 shows several spot welds.

The joint strength of the lap-welded alloys employing seam welds, as compared with the ultimate strength of the as-received metal is shown in Table 1. Joint strength was determined in pounds per inch of specimen width rather than pounds per square inch of interfacial area since it was extremely difficult to determine the area of the joint interface in many specimens.

The joint strength of aluminum alloys 2024-T3 and 6061-T6 as well as magnesium alloy AZ31B-0 and copper are essentially equal to the tensile strength of the respective base materials. For these materials, the spread exhibited by the welded joints approximated that exhibited by the base metals.

During the welding operation, plastic deformation occurred in each joint and reduced the thickness of the overlap to some extent. If these reduced cross sectional areas were taken into account, the strength values for lap welds in aluminum alloy 5083-H24 and 1020 steel may have more nearly approached their base metal strengths. The strength of the clad 7075-T6 weldment, however, varied considerably. All of the tensile shear specimens except those of the clad 7075-T6 alloy failed outside the weld.

TABLE 1
COMPARISON BETWEEN STRENGTH OF UNWELDED AND EXPLOSIVE WELDED BASE METALS

Material	Thickness (in.)	Base Metal or Weld	Load (pounds/in.) Average	Maximum	Minimum
2024-T3	0.062	Base Metal	4166	4213	4148
		Weld	4103	4206	3916
2219-T6	0.090	Base Metal	5660	5685	5647
		Weld	5149	5573	4888
5083-H24	0.090	Base Metal	4906	4919	4888
		Weld	4727	4852	4471
6061-T6	0.090	Base Metal	4260	4271	4224
		Weld	4257	4342	3991
Clad 7075-T6	0.090	Base Metal	6942	6980	6879
		Weld	5612	6782	3373
1020 Steel	0.020	Base Metal	904	909	900
		Weld	845	863	819
Mg Alloy AZ31B-0	0.062	Base Metal	2362	2379	2354
		Weld	2354	2382	2287
Copper	0.040	Base Metal	1260	1263	1259
		Weld	1283	1289	1264

JOINT QUALITY

The quality of explosively welded joints has been determined non-destructively by visual examinations, ultrasonic inspection and radiography. Destructive means include the peel test, bend test and tensile-shear test for determining the mechanical strength of joints. Metallography and hardness surveys also have been used to assess the quality of the weld and surrounding area.

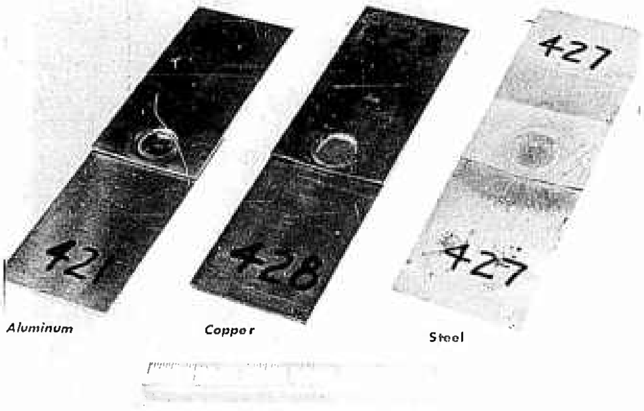

Fig. 9 Explosively spot welded, lap joints in three base metals

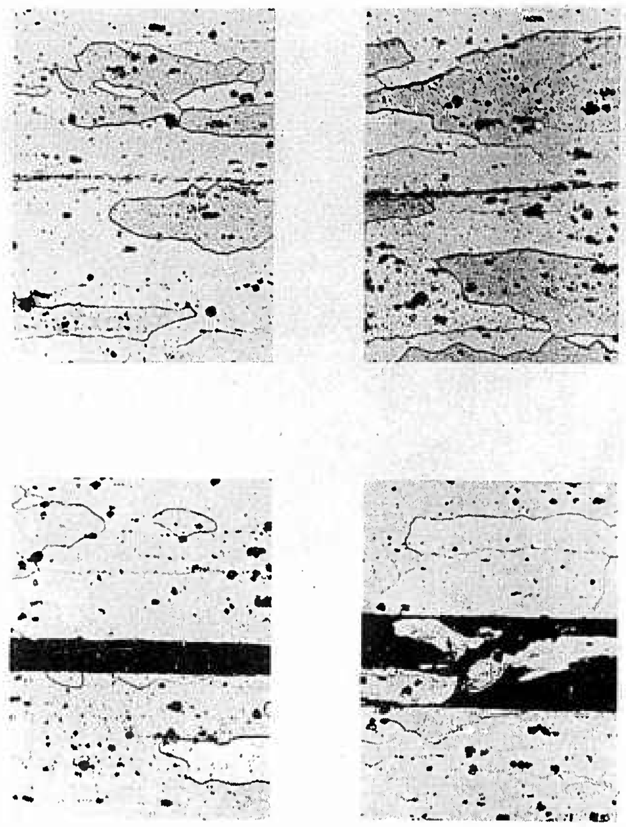

Fig. 10 Comparison between amplitude of ultrasonic signal and weld quality

A (top left): amplitude = 1.2
B (top right): amplitude = 0.7
C (bottom left): amplitude = 0.2
D (bottom right): amplitude = 0 X500

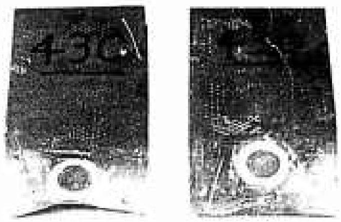

Fig. 11 Chisel tested spot weld in 1/16-in-thick, half-hard copper

Non-Destructive Tests

Visual Characteristics. Some measure of quality may be determined visually by observing the continuity of the joint at the edges. Gross irregularities on the surface such as excessive pitting, gouging, surface cracking, and deformation are indicative of poor quality. These defects can be minimized if not entirely eliminated through the use of appropriate welding procedures.

Internal Characteristics. Somewhat limited studies have shown promise that ultrasonic inspection can detect discontinuities or lack of bonding at the weld interface. A correlation was obtained between the amplitude of the ultrasonic signal and the amount of separation at the weld interface (1). The amplitude of the signal decreased as weld quality decreased and as the distance between the panels increased as shown in Fig.10. The figure shows four zones of the same lap joint with the corresponding signal height for each region.

The study, furthermore, revealed that factors other than weld quality such as the curvature and surface finish of the weldment could influence the ultrasonic signal. It was concluded that if weldments exhibiting severe distortion or varying surface finishes were ultrasonically examined, without compensating for these discrepancies, misleading results might be obtained.

Radiography has been employed to detect defects and has shown some cracking. It has also appeared to have shown the internal contour of spot welds. The existence of surface indentations, however, has partially obscured the image so that the results of radiography appear to be questionable. Radiographic inspection of seam welded joints also disclosed only visible surface irregularities and did not disclose known discontinuities in the joint.

Destructive Tests

Peel Test. The soundness of explosive welds also has been determined by destructive tests such as the peel or chisel test. These tests are conducted by peeling one member back against the weld or by driving a chisel between the members until failure occurs around the periphery of the weld, through the weld interface, or a combination of both. Any lack of bonding is noted.

The result of a chisel test on a spot weld in 1/16 in. thick, half-hard copper is shown in Fig. 11. Although the weld was separated with diffi-

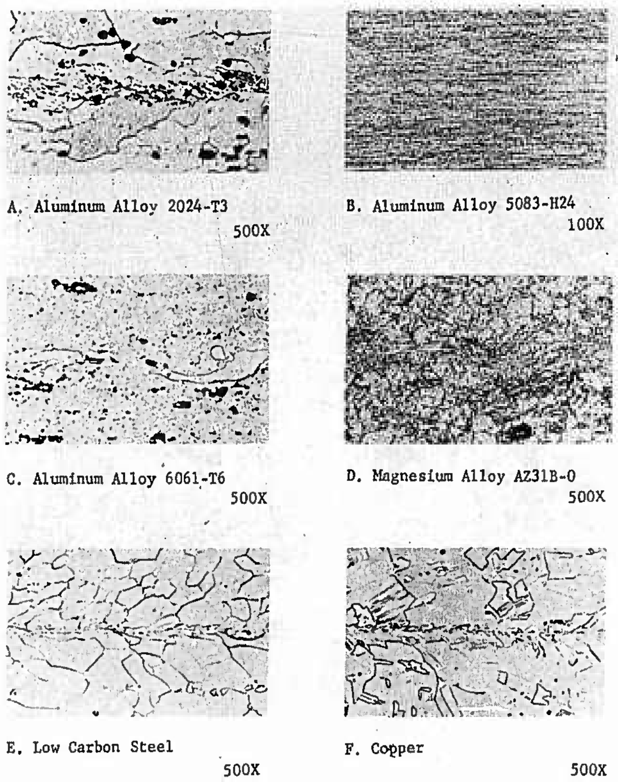

Fig. 12 Microstructures of weld interfaces in explosively welded materials

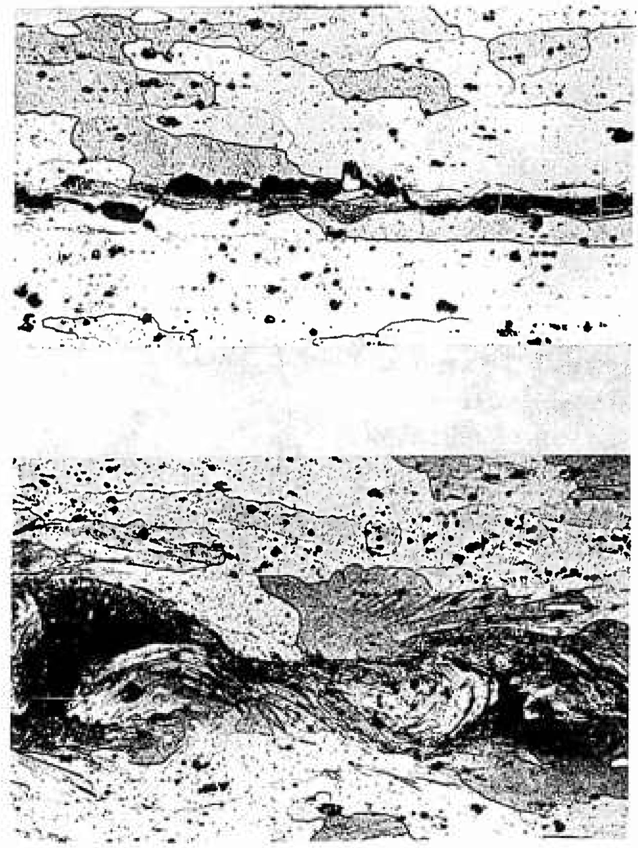

Fig. 13 Microstructure observed in low strength explosive welds in 2024-T3 aluminum alloy. A (top): fractured interface; B (bottom): partially bonded, wave-shaped interface; X500

culty (as evidenced by chisel marks on the panels), its center was not bonded.

Metallography. The weld interface of several explosively bonded materials as revealed at higher magnifications by an optical microscope is shown in Fig.12. These microstructures are representative of joints having good tensile shear strengths. An explosive weld is shown in a high strength, 2000 series aluminum alloy in Fig.12A. In Fig.12B, the interface of the 5000 series aluminum alloy was so well bonded that it was difficult to find. Zones similar to the light areas in Fig.12C have been reported to be solidified melt (10). The interface of an explosively welded magnesium alloy is shown in Fig.12D. A low-carbon steel interface is illustrated in Fig.12E and a copper interface in Fig.12F. Other microstructures also were observed in these specimens indicating considerable variation across the welded interfaces.

The structure of a low strength joint in aluminum alloy 2024-T3 is shown in Fig.13 (1). It can be seen that the weld exhibited cracking and a partially bonded wave shaped interface.

Fine discontinuities which could not be adequately observed with the optical microscope have also been noted in explosively bonded joints. Since it was desirable to know whether the irregularities were microstructure or defects such as cracking, they were identified with the electron microscope which has a higher resolving power. For example, consider the island-like structure in the cladding of Fig.14A. This photomicrograph shows an explosive weld in 1/16-in-thick alclad aluminum alloy 2024-0. It was not determined with certainty whether the periphery of the island were a crack or solid material when this area was examined up to X1500. The electron microscope, however, revealed that the periphery of the island was composed of solid material. A reproduction of the structure revealed by the electron microscope is shown in Fig.14B. The periphery of the island is the line indicated by the arrows. The microstructure above the line represents cladding outside the island and the structure below the line reveals that the island was composed of clad material.

Tensile Shear Strength. The quality of an explosive welded joint may be evaluated, within limits, by its tensile shear strength and mode of failure. Factors associated with the structure of the joint such as workhardening may increase the strength of the weld above that of the base metal whereas structural discontinuities such as crack-

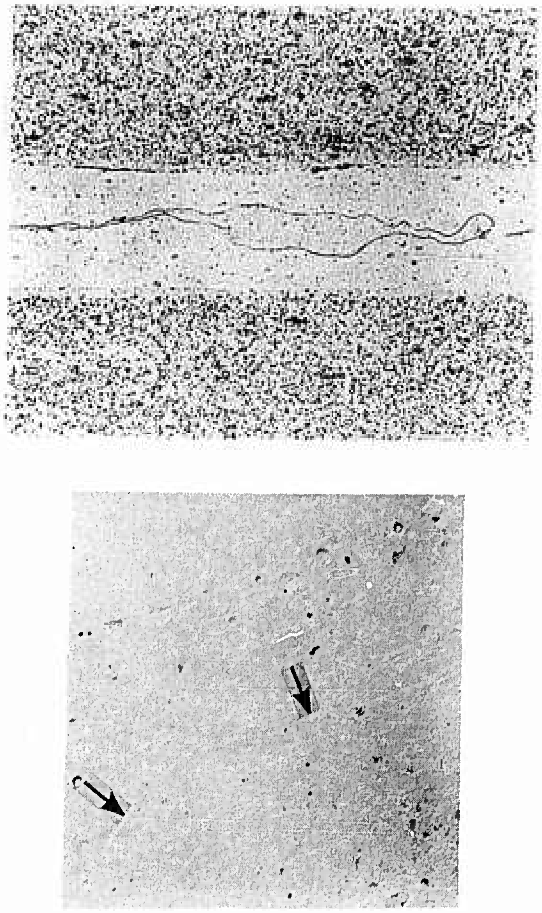

Fig. 14 Structure in explosively welded 1/16-in-thick alclad aluminum alloy 2024-0. A (top): X500 B (bottom): X5600

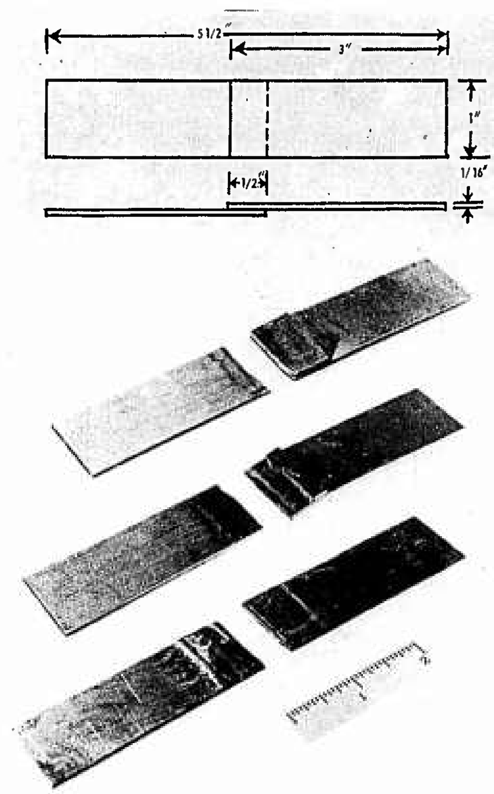

Fig. 15 Tensile shear tests of explosive seam welds in lap joints. A (top): tensile shear specimen; B (bottom): mode of failure

ing and lack of bonding can lower the base metal properties. The tensile shear strengths of a number of explosively welded materials were discussed previously.

The strength values were obtained from the tensile shear specimen shown in Fig.15A. Mode of failure exhibited by this specimen when seam welded is shown in Fig.15B. The lower specimen sheared through the weld and the middle specimen failed by a combination of tensile and shear within the overlap. The upper specimen failed through the base metal, adjacent to the overlap. This type of failure was characteristic of the higher strength specimens. Although these joints were seam welded, explosive spot welds may also exhibit somewhat similar failures. Two spot welded lap joints which failed outside the weld area are shown in Fig.16.

Hardness. The effects of explosive welding on base metal characteristics may be determined by hardness surveys. Pearson and Hayes (7) have reported base metal combinations such as steel to tantalum and tantalum to itself were hardened extensively at the weld interface due to alloying or the formation of a new phase. It was further reported that some metal systems including copper and monel exhibited interfacial hardnesses lower than that in the rest of the joint. This was attributed to annealing during welding or the formation of dendritic regions.

Hardness changes were also detected in metal systems that appeared similar to the as received material upon being examined with the optical microscope. It was reported that stainless steel, molybdenum and René 41 exhibited regions of high hardness in the weld interface without any basic change in the structure of the metal.

The base material away from the interface for all of these materials, however, was reported work hardened by the welding operation. The degree of hardening varied according to the material combination.

Bend. The ductility of a welded joint and defects such as cracking in the weldment can be determined to some extent by bend tests. As an example, a 1-in-wide, longitudinal bend specimen was fabricated from an explosively welded lap joint in 1/16-in. aluminum alloy 2024-T3. The specimen was bent cold around a 3/4-in-dia mandrel for about 36 deg before cracking occurred as shown in Fig.17. Another specimen made with the same welding con-

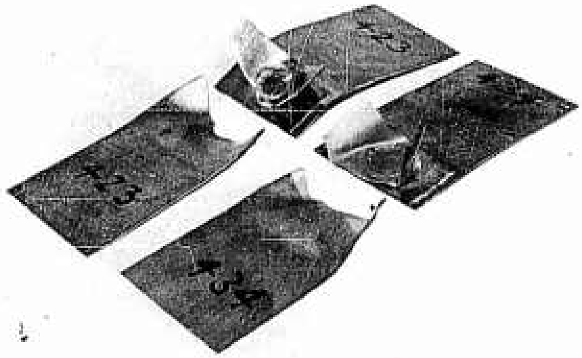

Fig. 16 Tensile shear tests of explosive spot welds in lap joints No. 423 copper to copper; No. 434 steel to copper

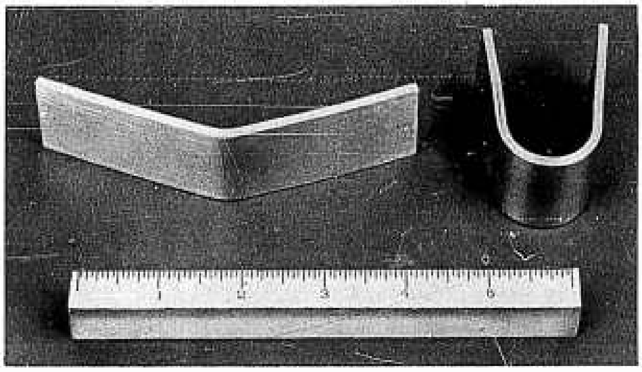

Fig. 17 Guided bend specimens in explosively welded aluminum alloy 2024

ditions was annealed and then bent cold through 180 degrees around the same mandrel, Fig.17.

APPLICATIONS

The feasibility of explosive welding has been demonstrated and procedures and techniques are being studied by both government and industry with particular reference in some instances to specific applications. This effort to apply the process, of course, does not preclude the need for longer range studies of a research nature but does highlight the interest in exploring its possibilities for satisfying certain immediate joining situations.

As explosive welding is developed, the number and type of applications that might be served will probably grow. At the present time, there are several likely applications. The process appears useful for joining relatively thin sheet to thicker sheet or plate such as is shown in Fig.18. This type of weldment could represent the joining of attachments to structural members including the

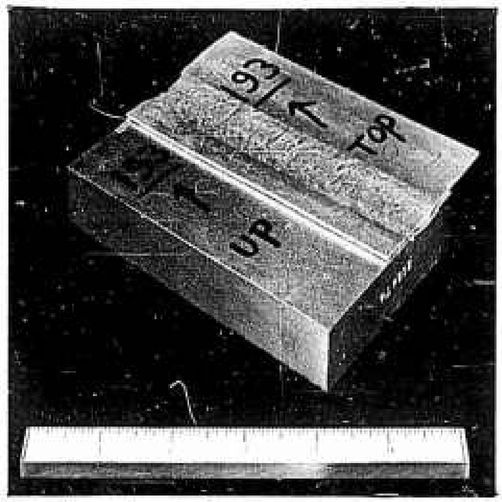

Fig. 18 1/16-in-thick 2024-T3 aluminum-alloy panel explosively welded to 1-in-thick 2024-T-4 aluminum-alloy plate

joining of brackets to pressure vessels or boxes, panels or clips to metal bulkheads, decking or other massive structures.

Laminated materials may be seam or spot welded as shown in Fig.19. Since explosive welding is one of few welding processes that are capable of making area welds or edge joints it may have a very significant place in the fabrication of items requiring laminated and composite type joints and structures, the fabrication of clad materials, or transition couplings.

Cylindrical components may also be explosively welded as shown in Fig.20. The specimen on the left was a section from two pieces of aluminum tubing which were welded together. Although the weld is intermittent, the sample does indicate the possibility of explosive welding this type of configuration. The other specimen shows several aluminum tubes bonded inside an aluminum pipe. These results suggest that pipe and tubing can be joined by explosive welding for applications such as gun liners, heat exchangers, filters, casings and sleeves.

Explosive welding may also be useful as a method for fabricating and repairing structures in locations that would be inaccessible or inconvenient for other processes. It might also prove useful for welding a limited number of items which might not warrant the procurement of elaborate, expensive equipment.

CONCLUSIONS

It may be concluded that:

1 Area, spot and seam welds can be produced with the explosive welding process.

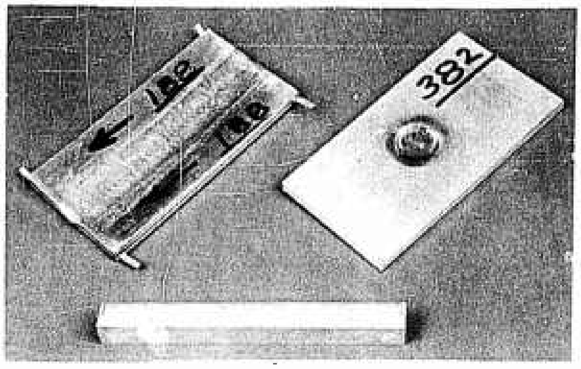

Fig. 19 Explosive seam and spot welds in aluminum alloy 2024-T3, multilayer specimens

2 Explosive welding appears capable of producing edge, lap and tee joints and shows promise for making corner and butt joints.

3 Explosive welding can join a variety of metals and alloys in similar and dissimilar combinations.

4 The quality of explosively welded joints may be determined by a number of destructive and nondestructive tests.

5 Explosive welding offers considerable potential for use in a variety of civilian and military applications.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Mr. H. Markus for granting permission to publish this work and to Messrs. F.W. Hussey and I.G. Betz for their technical assistance in the preparation of this paper.

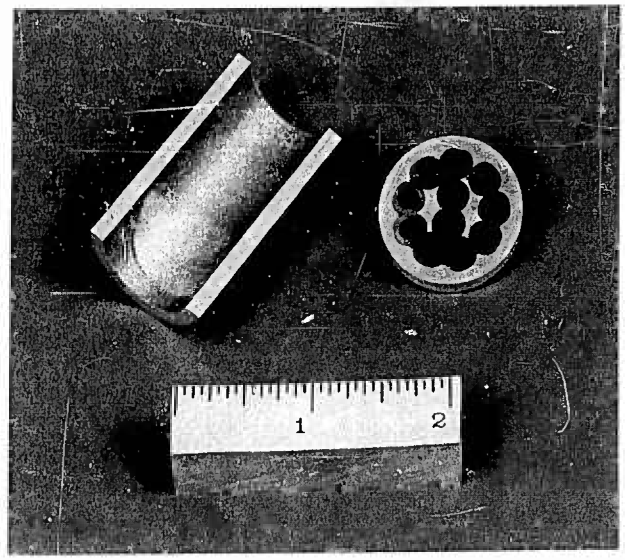

Fig. 20 Explosively bonded, cylindrical aluminum components

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3. REPORT TITLE EXPLOSIVE WELDING	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Research report	
5. AUTHOR(S) (Last name, first name, initial) ADDISON, Harry J., Jr.	
6. REPORT DATE May 1964	7a. TOTAL NO. OF PAGES 15 7b. NO. OF REFS 10
8a. CONTRACT OR GRANT NO. AMCMS Code 5025.11.842 b. PROJECT NO. DA Project 1-A-0-24401-A-110 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) FA Report A64-13 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) Paper No.: 64-MD-47 (Amer Soc Mech Eng)
10. AVAILABILITY/LIMITATION NOTICES Qualified requesters may obtain copies of this report from DDC.	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY AMCRD-RS-CM-M

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Explosive welding occurs when adjacent surfaces of appropriately positioned metals are properly thrust together by energy released from an explosive source. The procedure consists essentially of locating the metal members being welded between an explosive charge and an anvil with the lower member resting on the anvil. Explosive welding can be used for spot and seam welding and cladding. Lap, tee, and edge joints (such as is experienced in cladding) have been fabricated. Corner and butt joints are feasible. Tensile-shear strengths approaching that of the base metal have been obtained in various materials in seam-welded lap joints. Explosive spot welds have failed outside the nugget. Explosive welding is feasible and offers possibilities as a future fabrication method.

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